Modelling climate-vegetation interactions during the last and current interglacials

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Summary

Vegetation is one of the important components of the climate system and interacts with the atmosphere on a time scale ranging from hours to centuries at both regional and global scales. Plants respond to climate change when the amplitudes of climatic change exceed the tolerance of the species. In the meantime, vegetation impacts on the atmosphere through changes in surface conditions, such as in albedo and soil moisture (biogeophysical feedbacks) and changes in carbon and other nutrient cycles. Studying these interactions between climate and vegetation under past climate change provides insights into how vegetation responds to different climate conditions, and into magnitudes of the corresponding vegetation feedbacks to the climate system. The Earth's climate has oscillated between warmer interglacial and colder glacial climates over the past 2.6 million years. These past climate change provide opportunities for studies on climate-vegetation interactions.

We investigated climate-vegetation interactions with the climate model iLOVECLIM and two Dynamical Global Vegetation Models (DGVMs: LPJ-GUESS and VECODE) under four different CO_2 scenarios, from very low to very high, and four past climate change, including the 8.2 ka BP (kilo annum before present: 1950 AD) cooling event, the mid-Holocene time-slice, and long-term climate evolutions during the Holocene (~11.7 ka BP - present) and the Last Interglacial (LIG, 130-116 ka BP). The two DGVMs simulate vegetation dynamics in contrasting complexity, with LPJ-GUESS being much more complex than VECODE. Using these two DGVMs thus gives us information about the impacts of model-dependence on interactions between climate and vegetation. We first conducted sets of vegetation simulations with both DGVMs under identical climate conditions (the mid-Holocene (6 ka BP), the pre-industrial state with halved CO_2 levels (140 parts per million, or ppm), doubled CO_2 (560 ppm), and quadrupled CO_2 (1120 ppm)) to investigate sensitivities of these two DGVMs to changing climate and CO_2 levels and assess the impact of their respective complexity on these sensitivities. Compared to pre-industrial era, the climate at 6 ka BP is treated as a benchmark of warm conditions during the Holocene in the Northern Hemisphere (NH) because of the higher summer insolation, while the level of atmospheric CO_2 affects climate and vegetation as one type of greenhouse gases and resources, respectively. After having a basic understanding of these two DGVMs, we simulated the vegetation responses to the 8.2 ka BP cooling event and compared the simulated vegetation changes to pollen records over Europe and Northern Africa. The 8.2 ka BP event has been confirmed to be the highest magnitude abrupt climate event at the northern mid- to high- latitudes during the

Holocene, featured by declines of mean annual temperature between -0.6℃ to -1.2℃ around the circum-North Atlantic for 100 to 150 years and drier conditions over the Mediterranean and the NH tropics. Moreover, we assessed the evolution of vegetation during the LIG and the magnitude of both regional and global dynamical vegetation feedbacks using again the iLOVECLIM climate model with either VECODE or LPJ-GUESS coupled as vegetation component. Compared to the pre-industrial conditions, about 2℃ global warming and higher sea level during the early LIG are suggested by proxy-based reconstructions. Additionally, we apply the same climate model in combination with these two DGVMs to simulate climate-vegetation interactions during the Holocene. Compared to the Holocene, an analogue for green and moist North Africa exists during the early LIG, followed by desertification at different rates in response to declines of summer insolation in the NH. Therefore, a comparison of the patterns of North African vegetation evolutions and their feedbacks between the Holocene and the LIG was performed to understand the abruptness of climate and vegetation changes in North Africa and the mechanisms of these changes.

With effects of climate forcings from iLOVECLIM forced by orbital-scale insolation and changes in greenhouse gas (GHG) concentrations, both DGVMs suggest consistent features of vegetation changes from the mid-Holocene to the pre-industrial. The patterns of vegetation responses to the more extreme varying CO_2 scenarios were more variable, as LPJ-GUESS, with more complexity, suggests stronger magnitudes of vegetation responses to varying CO_2 levels than VECODE, in particular in tropical regions. The sensitivity of the global Leaf Area Index (LAI) in both DGVMs decreases with the increasing atmospheric CO_2 from the pre-industrial level to the 4*CO_2 scenario. Moreover, the tropical vegetation sensitivities, defined as the changes in tree-cover per degree of temperature anomaly, vary from 0.5 ($℃^{-1}$), 0.25 ($℃^{-1}$) to 0.15 ($℃^{-1}$) under ½*CO_2, 2*CO_2, and 4*CO_2 scenarios in LPJ-GUESS, while these values are around 0.05 ($℃^{-1}$) for all scenarios in VECODE. The higher sensitivity of LPJ-GUESS to CO_2 concentrations is related to the inclusion of more detailed ecophysiological processes compared to VECODE. In addition, the complexity of eco-physiological processes in DGVMs also impacts on vegetation requirements for rainfall due to the physiological effects that more efficient water use of vegetation is facilitated under elevated atmospheric CO_2 concentration. The required rainfall for dominant development of tropical trees ranges from around 800 mm under the 4*CO_2 scenario (1120 ppm) to about 1500 mm under pre-industrial CO_2 forcing (280 ppm) in LPJ-GUESS. In contrast, this requirement does not change significantly in VECODE due to its independence of vegetation fraction to atmospheric CO_2 levels.

In addition to the vegetation responses to climate change with different levels of CO_2 concentrations, vegetation (represented by PFTs: Plant Functional Types) over Europe and North Africa responds to abrupt cooling during the 8.2 ka BP event in different magnitudes and timing with different impact factors. During this cooling event, the decreased temperature drives reductions of the temperate broad-leaved summer-green trees (TempBS) fraction by 17% and 14% within 50 years in Northwestern and Northeastern Europe, respectively, and significant expansions of boreal needle-leaved evergreen trees (BoNE) in both regions. In Western Europe, due to changes in both temperature and precipitation, TempBS decreases by 7% in about 20 years, while temperate broad-leaved evergreen trees (TempBE) declines by only 2% in around 60 years. In Eastern Europe, only TempBS decreases by 5% at the beginning of the event. In Southern Europe, grasses expand at the expense of TempBE, and the tropical trees (only 2%) disappear immediately when the cooling starts. In North Africa, grass cover decreases by 15% in 50 years mainly in response to the >50% decreases in summer precipitation, followed by a minor expansion (by 2%) of TempBE. After the 8.2 ka BP event, most PFTs return to their pre-perturbed state, except for TempBS, which does not recover in Northeastern, Western and Eastern Europe. The unrecovered vegetation in these regions implies the possibility of different vegetation compositions under similar climate conditions, as a long-lasting vegetation response to an abrupt climate perturbation through eco-physiological and ecosystem demographic processes, e.g., plant competition. Our modelled vegetation responses indicate a general agreement with pollen records from Europe, but a latitudinal gradient with more pronounced vegetation responses to the severe cooling in the north and weaker responses to less cooling in the south is not seen in pollen records.

On the long-term scale, positive impacts of dynamic vegetation in the LIG simulations suggest much better agreements with reconstructed temperature based on proxies than the LIG simulation with fixed pre-industrial vegetation, in particular in the high latitudes and the tropics. In boreal regions, trees extend further north and tree covers are up to 50% higher in 125 ka BP relative to pre-industrial conditions, resulting in a positive surface temperature anomaly (>2.5℃) compared to pre-industrial. Likewise, in North Africa, positive surface temperature anomalies (~1.5℃) are found. A strong annual mean temperature trend at all latitudes during the LIG in simulations with dynamical vegetation indicates a warming effect of vegetation at a global scale, but these simulations still underestimate the change in temperature compared to proxy-based reconstructions.

Comparisons of vegetation transitions in North Africa during the LIG and the Holocene reveal nearly linear declines of vegetation cover corresponding to the decline in summer insolation at 20°N during both interglacials. During the early LIG and early Holocene, vegetation cover in the Sahara keeps a relatively high level, with >70% and about 60%, respectively. In response to the declines of the summer insolation at 20°N, vegetation cover is reduced during both interglacials and the rates of this reduction peaks at 25%/ka and 10%/ka at around 122 ka BP and 6 ka, respectively. The process of desertification is accelerated when the magnitude of positive vegetation-albedo feedbacks on precipitation cannot offset the moisture deficit due to decreased summer insolation. The abrupt vegetation transition during the LIG is a result of strong vegetation feedback and rapidly decreased precipitation, while the gradual vegetation transition during the Holocene is related to the strong vegetation feedback and gradual declines in precipitation.

Compared to desert, the vegetated surface is featured by a lower albedo, which enhances the absorption of solar radiation and therefore leads to a warmer surface. In North Africa, the warmer vegetated surface than desert induces larger land-sea temperature contrasts, leading to a stronger African summer monsoon, which promotes vegetation development because of the enhanced precipitation. During the early LIG and Holocene, vegetation strengthens precipitation by a factor of 2 to 3 through this vegetation-albedo feedback when the vegetation cover is greater than 60%. The effects of vegetation feedbacks to climate decrease in phase as vegetation cover declines during both interglacials. The effects of vegetation feedbacks on precipitation during the LIG and Holocene suggest more gradual declines in experiments with dynamic vegetation from LPJ-GUESS than VECODE. The key factor adjusting the magnitude of the vegetation-albedo feedback is the vegetation cover and the differences of surface albedo between vegetated and bare desert soil surface. The summer insolation at 20°N plays a central role in driving the incoming moisture transport by the atmosphere, thereby the amount of precipitation and the development of vegetation in North Africa. In the meantime, the positive vegetation-albedo feedback enhanced the amount of precipitation during the early periods of both interglacials and the weakening of this feedback afterwards accelerates vegetation transitions. Also, the abruptness of vegetation transitions is related to the complexity of the vegetation components in our climate model since the higher complexity of the LPJ-GUESS vegetation model involves a larger diversity and provides vegetation features in more detail.

Similar to the vegetation impacts on global atmosphere circulations during the Holocene, the vegetated Sahara during the LIG has a positive impact on surface temperature globally. Compared with desert, the vegetated Sahara leads to an increase in surface temperature and a decline in surface air pressure due to local feedbacks, thereby enhancing mid-latitude westerlies as a result of increased latitudinal temperature and pressure gradients, leading to an increase in the amount of heat transported by the atmosphere from tropical regions to the Arctic. The green Sahara feedback at 125 ka BP provides up to 30% of the total contribution of global vegetation feedbacks to high latitudinal warming.